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Estimating Densities of Small Fishes and Decapod Crustaceans in Shallow Estuarine Habitats: A Review of Sampling Design With Focus on Gear Selection

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ABSTRACT: Shallow estuarine habitats often support large populations of small nekton (fishes and decapod crustaceans), but unique characteristics of these habitats make sampling these nekton populations difficult. We discuss development of sampling designs and evaluate some commonly used devices for quantitatively sampling nekton populations. Important considerations of the sampling design include the size and number of samples, their distribution in time and space, and control of tide level. High, stable catch efficiency should be the most important gear characteristic considered when selecting a sampling device to quantify nekton densities. However, the most commonly used gears in studies of estuarine habitats (trawls and seines) have low, variable catch efficiency. Problems with consistently low catch efficiency can be corrected, but large unpredictable variations in this gear characteristic pose a much more difficult challenge. Study results may be biased if the variability in catch efficiency is related to the treatments or habitat characteristics being measured in the sampling design. Enclosure devices, such as throw traps and drop samplers, have fewer variables influencing catch efficiency than do towed nets (i.e., trawls and seines); and the catch efficiency of these enclosure samplers does not appear to vary substantially with habitat characteristics typical of shallow estuarine areas (e.g., presence of vegetation). The area enclosed by these samplers is often small, but increasing the sample number can generally compensate for this limitation. We recommend using enclosure samplers for estimating densities of small nekton in shallow estuarine habitats because these samplers provide the most reliable quantitative data, and the results of studies using these samplers should be comparable. Many kinds of enclosure samplers are now available, and specific requirements of a project will dictate which gear should be selected.

Introduction

Shallow estuarine habitats that include emergent marsh, submerged aquatic vegetation, mangroves, and tidal flats are extremely productive and often support large nekton populations. Because of this productivity, these habitats have been the focus of much ecological research. Study objectives often involve an assessment of relative habitat value through interhabitat comparisons of nekton densities or an examination of temporal trends in population size within habitats. As in most ecological field research, sampling the abundance of animal populations is pivotal, and a wide array of sampling strategies and gear types have been developed for this purpose.

The unique characteristics of shallow estuarine habitats must be considered when designing a sampling program. All of these habitats are either intertidal or adjacent to intertidal bottom. As water levels fluctuate with the tide or with other hydrodynamic processes, animal distributions among habitats change (Peterson and Turner 1994), and estimates of density (numbers per square meter of bottom) can be greatly affected. This redistribution of nekton with each tide must be considered when estimating population size. Heterogeneity within habitats and the dramatic changes in the physical environment associated with estuarine systems also contribute to sampling problems.

One of the most important decisions in developing a sampling program is gear selection. Gear selection should be based on requirements for data and specific objectives of the study, not on the ease of deployment, on historical efforts, or because of limited exposure or training in the various gears available. Many types of sampling gear and

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techniques have been developed for use in estuarine habitats, but the collection of quantitative (both accurate and precise) data remains a major challenge. Accuracy and precision are both affected by catch efficiency, and stability in catch efficiency may be the most important requirement in a gear. The use of gear that characteristically exhibit large and unpredictable variations in catch efficiency makes habitat comparisons unreliable and decreases the ability to detect statistical differences in the data.

In this paper we review important considerations that are necessary to successfully carry out a sampling project for estimating densities and population abundances of small nekton in shallow estuarine habitats. Although we discuss various aspects of the topic, we emphasize the problem of gear selection, one of the most important considerations of a sampling design. We develop a set of desirable gear characteristics and evaluate the suitability of some common sampling devices.

Targeted Habitats and Species

This paper is directed specifically toward quantitatively sampling small fishes and decapod crustaceans in shallow (< 1 m deep) areas of estuaries, although in many instances our conclusions can be more broadly applied. The shallow regions of estuaries contain some of the most productive fishery habitats, including tidal marshes, seagrass beds, mangroves, tidal flats, and oyster reefs (Pihl and Rosenberg 1982; Weinstein 1982). Habitat is defined broadly here as an area inhabited by nekton (Peters and Cross 1992), and habitats are generally characterized on the basis of hydrology, substrate type, and dominant vegetation. Hydrology is mainly determined by elevation, and habitats are either subtidal (i.e., continuously flooded) or intertidal (i.e., alternately inundated and drained). Habitat substrates are defined by sediment grain size, the presence of shell or rock, and the proportion of organic material. Inorganic sediments may vary greatly in grain size composition (proportion of sand, silt, and clay). Other substrates are composed mostly of partially-decayed plant material, shell and shell hash, or rock. For example, oyster reefs are habitats with substrates consisting almost entirely of shell from living and dead oysters. A wide variety of vegetated habitats exist in both subtidal and intertidal areas. In subtidal areas, seagrasses and many other species of submerged aquatic vegetation (SAV) occur. Intertidal areas support SAV, mangroves, and emergent marsh species. Major determinants of plant species composition are geographic region, salinity, and hydroperiod (Mitsch and Gosselink 1986; Latham et al. 1994); species richness (number of plant species) generally increases as salinity decreases (Chabreck 1971, 1972; Gosselink 1984). All shallow estuarine habitats support fishes and crustaceans, although support varies among habitats in kind and degree.

Small (< 100 mm TL) fishes and decapod crustaceans have been targeted in this review for a variety of reasons. These organisms are abundant in shallow estuarine habitats, thus population sizes are relatively easy to estimate (Kjelson 1977). The group includes all life stages of some resident species plus the young of transient species that use estuarine habitats as nursery areas. Many of these transient species are of special interest because of their recreational and commercial fishery importance. Density estimates of the young of economically important species can be used as a measure of a habitat's relative nursery value for fishery species by comparison to densities in other nearby habitats (Pearcy and Myers 1974; Zimmerman and Minello 1984; Sogard and Able 1991; Baltz et al. 1993). The distribution of young fishery species is more likely to accurately reflect habitat value than the distributions of adults, which may be affected by local fishing pressure and greater variance in density. Large juveniles and adults are also more difficult to sample quantitatively because they are less abundant, more motile, and more widely distributed (Kjelson 1977). Finally, the best sampling methods available today have been developed to quantitatively sample our targeted size group.

Sampling Design

Clearly defining the goals of an ecological study is a critical exercise that is often neglected. Without specific goals, research projects are likely to have ambiguous results (Green 1979). Each study goal should be converted into a research question and refined into specific objectives. One goal may provoke several objectives, and the objectives should narrow the scope of the research goal to a tractable problem. Testable hypotheses should then be developed from the objectives, and the sampling protocol should be designed to test these hypotheses.

Shallow estuarine habitats have some unique characteristics that must be considered in designing a sampling program. The effect of water-level fluctuations must be considered in estimating the abundance of nekton in these habitats. Changing water levels, either due to tidal fluctuations, meteorological effects, water-level control structures, or alterations in freshwater inflow can drastically alter density estimates. The rising tide in coastal areas greatly expands the amount of flooded bottom area in a basin. As examples, aquatic habitat was estimated to expand fourfold to ninefold when a tidal freshwater marsh flooded (McIvor et al.

1989), and a four-to-one ratio of intertidal to subtidal area was estimated for a salt marsh system (Pomeroy and Imberger 1981). Assuming an even distribution of animals over the flooded area, animal densities will decrease as the tide rises and floods intertidal habitat. If water level is not considered in comparing density estimates among sites or over time, spatial and temporal differences in animal abundance will be indistinguishable from density changes due to this water-level effect (Vance and Staples 1992; Loftus and Eklund 1994). This concentrating factor at low water levels is often ignored in sampling designs. To complicate the situation, many animals such as killifishes (Family Cyprinodontidae), grass shrimp, (*Palaemonetes* spp.), brown shrimp (*Penaeus aztecus*), blue crab (*Callinectes sapidus*), and spotted seatrout (*Cynoscion nebulosus*) are attracted to shoreline emergent vegetation when it becomes accessible at high water levels (Zimmerman and Minello 1984; Loftus and Eklund 1994; Peterson and Turner 1994). If sampling efforts are concentrated in the adjacent subtidal habitats, density estimates for these organisms will increase dramatically as water levels drop and animals are forced out of shoreline vegetation (Loftus and Eklund 1994; Peterson and Turner 1994).

The most unbiased picture of habitat use at a site would require sampling at all water levels in proportion to the time these water levels occur in the study area. This approach, however, would increase within-habitat sample variances and require a large effort to detect patterns of habitat utilization. A practical solution to the problem is to sample all habitats of interest at similar water levels. Inferences must be limited to that water level; but this type of sampling design allows unbiased comparisons of habitat utilization. Low-water sampling may be most desirable if only subtidal habitats are targeted in the study, because under such conditions animals will be precluded from using shoreline habitats (e.g., flooded vegetation); and densities in subtidal habitats will be relatively high. However, in situations where comparisons are desired between intertidal and subtidal habitats, animal densities should be sampled at high tide when the habitats are equally accessible to aquatic organisms.

When comparing utilization patterns, habitats of interest should be clearly defined. Frequently, generally-recognized habitats are really mosaics of habitats (environmental strata) that have different characteristics and different utilization patterns. Sampling of animal populations may often need to be stratified in relation to these environmental strata. For example, emergent marsh may be stratified into edge or inner-marsh habitat, low elevation or high elevation habitat, or into strata dominated by different macrophyte species. Estimates of animal populations in intertidal marsh containing a variety of habitats may be biased if samples are restricted to only one or two of these habitats. Habitat mapping can be used to define strata and allocate sampling effort. Once the habitats of interest are identified, we recommend the random selection of sampling sites within each habitat. This sample site identification is best done with a gridded map of the area. Frequently the argument is made that this type of random assignment may miss some important location within the habitat or strata of interest; such arguments, however, are generally founded on inadequate identification of important strata. Systematic sampling is defensible as an alternative to random sampling. A systematic allocation of sampling sites simply means that sites are evenly spaced across the habitat area. These sampling sites are often fixed for future use. Locating systematic or evenly spaced sampling sites over a strata, however, should be done carefully (and best, remotely). It is not acceptable to cruise the sampling area and pick sampling sites because they 'look good,' they are easily accessible, or they are easy to sample. These site selection techniques are highly subject to bias, and the sampling sites chosen in this manner are not likely to represent the habitat or strata as a whole.

Choosing the appropriate number of samples is dependent upon gear selection to some extent but also involves other considerations. Collecting too many samples wastes time and resources, and taking too few samples may result in a failure to accomplish the study objectives (Dixon and Garrett 1993). Deciding on the number of samples usually is a compromise between cost and sample precision (Johnson and Nielsen 1983; Pringle 1984). Increasing the number of samples may increase precision and the ability to distinguish among hypotheses. The sampling design should incorporate as few samples as possible and still have enough statistical power to detect differences among experimental treatments or other factors of interest. Procedures for determining the number of samples required are widely available (e.g., Sokal and Rohlf 1981; Bros and Cowell 1987; Goldstein 1989; Peterman 1990; Eckblad 1991; Fairweather 1991; Manly 1992; Hewitt et al. 1993). Briefly, an estimate of sample variance is used to calculate the number of samples necessary to detect a percentage difference between two means (e.g., control and treatment or two different habitats). Sample variances can be estimated from data collected during preliminary sampling, in a short pilot study, or from studies of similar estuarine habitats that are reported in the literature. The use of complex analysis of variance (ANOVA) designs and data transformations to meet ANOVA assumptions will often improve the capability of detecting differences among treatments.

Gear Selection

Selecting a sampling device is one of the most important steps in planning a study of estuarine animal populations. The sampling gear must be appropriate for the target species and habitats as well as for the overall objectives of the study. Ideally, the gear should be accurate and precise in estimating animal densities. Accuracy is the closeness of a mean density estimate to the true mean density of animals in a habitat, whereas precision is the closeness of repeated density estimates taken from the habitat (Sokal and Rohlf 1981). Gear catch efficiency, or the proportion of target animals collected from the sample unit area, is an important factor affecting sampling accuracy. Variability in catch efficiency can also affect sampling precision. Catch efficiency has two components: gear capture efficiency and recovery efficiency (Kjelson and Colby 1977). Gear capture efficiency is the proportion of target animals within the sample unit area that is enclosed or captured by the gear. Capture efficiency is reduced by gear avoidance, which may be active (e.g., animals in the path of the gear swim over or under it and avoid capture) or passive (e.g., gear may miss animals burrowed in the substrate or hiding in vegetation). Recovery efficiency is the proportion of target animals enclosed by or taken into the gear that is recovered from the sampling device and enumerated. Recovery efficiency is diminished, for example, if some animals within a sampler cannot be removed or if small organisms escape from a sampling device through large-mesh netting. The goal should be to select a gear with a high catch efficiency. Moderately efficient gear will also be adequate for accurately estimating population densities if catch efficiency is known and relatively stable (Kuipers et al. 1992). However, catch efficiency must be known and stable over the range of environmental conditions encountered in the study.

No gear is 100% efficient in capturing estuarine nekton, and the ability to measure catch efficiency is necessary for estimating actual densities and temporal changes in targeted populations from sampling data. It is also essential to measure catch efficiency under conditions (for dominant species, different habitats) that will be encountered in the field (Kjelson 1977). Catch efficiency has been measured in several ways. Mark-recapture studies (Loesch et al. 1976; Kjelson and Johnson 1978; Sullivan et al. 1985) and the use of rotenone or seining (Kjelson and Johnson 1973; Kushlan 1981) have been used to estimate 'actual' populations in a confined area (e.g., pond or area blocked by small-mesh net) for comparison with estimates made from samples collected by the gear to be tested. A problem with this approach is that estimates of the actual population may also be biased. This problem may be overcome by testing gear in a large isolated area into which a known number of animals have been added (Pihl and Rosenberg 1982; Zimmerman et al. 1986). Difficulty in measuring the two components of catch efficiency (recovery efficiency and capture efficiency) varies with gear type. Recovery efficiencies are relatively easy to measure in enclosure samplers using marked animals (Weinstein and Davis 1980; Matlock et al. 1982; Zimmerman et al. 1984; McIvor and Odum 1986; Thayer et al. 1987; Rozas and Odum 1987; Rozas 1992) or using depletion estimates (i.e., fitting the data from repeated recoveries within the sampler to an exponential decay function) (Kneib 1991; Connolly 1994). Measuring recovery efficiency for other types of sampling gear is more difficult. Directly measuring gear avoidance and capture efficiency is difficult for most gear but has been estimated visually in clear water for trawls (Workman et al. 1995) and a pop net (Larson et al. 1986).

Gear catch efficiency usually varies among habitats sampled, thus decisions on gear selection must be associated with targeted habitats. Any gear selected must be effective (i.e., have a high catch efficiency) throughout the sampling area, and catch efficiencies should be known for each habitat sampled. When the objective of a study is to compare nekton utilization of different habitats, we recommend using a gear that is equally efficient in all habitats to avoid the need for correction factors. Gear efficiency can also vary substantially within a habitat. If gear efficiency is high only in some of the targeted habitat (i.e., some environmental strata), population estimates may be biased in the strata where the device is ineffective unless a correction factor is used. If some strata within a habitat are avoided (not sampled) and densities are different in sampled and unsampled strata, the population estimates may not represent those of the targeted study area as a whole. For example, a throw trap may not be appropriate for sampling a marsh containing patches of dense emergent vegetation that render the devise ineffective even though the gear would perform satisfactorily in areas of the marsh where plants are sparse (Kushlan 1974; McIvor and Odum 1986).

Ease of standardization is an important quality of a sampling gear. Standardizing gear is necessary to ensure that catch efficiency does not vary due to changes in gear specifications or how a gear is used. Some gear are more difficult than others to standardize. In general, the fewer variables influencing gear efficiency the better. Devices with few variables influencing gear efficiency require less adjustment to maintain their effectiveness. This consideration is especially critical for large monitoring programs or research projects where more than one field crew must collect samples concurrently. In such circumstances, ease of standardization may be critical to the success of the project.

Another important aspect of any gear is the area sampled with each deployment (i.e., the sample unit area). The appropriate size of the sample unit area is dependent on the density, distribution, behavior, and size of targeted species; and on the objectives of the study. In general, as the density of animals decreases or their distribution becomes more clumped, the total area sampled must be increased to estimate the population accurately (Kjelson 1977; Jacobsen and Kushlan 1987). Increasing the area sampled can be accomplished by taking more samples or enlarging the sample unit area. However, if the total area sampled is fixed (e.g., 100 m^2 within a habitat), many small samples will usually provide a better estimate of population abundance than fewer large samples (Lenarz and Adams 1980; Pringle 1984; Palmer and White 1994). Some consideration should also be given to animal behavior. To obtain representative samples of fast-swimming pelagic and schooling species, a larger sample unit area is required than for sedentary benthic and nonschooling animals (Kjelson and Johnson 1973; Kjelson et al. 1975; Gilmore et al. 1978). For a given type of gear, increasing the sample unit area will generally require more time and effort to collect and process individual samples; but the increase in effort is not necessarily proportional to the increase in sample unit area (Chick et al. 1992). Therefore, one challenge in developing a sampling design is balancing the sampler unit size with the sample number.

A major reason for using any quantitative sampling method is to determine animal densities for comparative purposes. Therefore, it is imperative that the sample unit area of a gear be easily determined. Because most animals are oriented to the bottom or to vegetative structure in shallow estuarine habitats, densities within habitats should be reported as number of organisms per unit area of bottom (e.g., individuals m^{-2}). However, the gear should effectively sample the entire water column, because the goal is to sample all animals in the sample area regardless of their position in the water column.

Effective operation of the gear should not depend on modifying the habitat prior to sampling, and disturbance in the sample area should be minimal. Changes to the site prior to sampling may bias samples, and the problem is especially severe where repeated sampling of the same site causes chronic deterioration of the habitat (Hoese and Jones 1963; Moseley and Copeland 1969; Kushlan 1974; Loftus and Eklund 1994) and statistical nonindependence of samples.

The cost of gear construction, sample collection, and sample processing should not be a primary consideration in selecting a gear type, but the reality of funding any sampling program makes cost an important factor. The selected gear should be easy to use and relatively inexpensive to construct, maintain, and operate (Wegener et al. 1973). Costs can be reduced by choosing gear that require only a small sampling crew and a short deployment time. This deployment time, or the time required to collect a sample, also affects the number of samples that can be collected. More samples can be taken using a faster sampling device, and additional samples can increase the precision of the data (Moseley and Copeland 1969; Kjelson et al. 1975). Sorting and processing a sample is usually much more costly in the overall budget than collecting the sample. Therefore, using a device that collects a relatively clean sample (i.e., small amount of extraneous material) that requires little sorting time is also an advantage. The cost of sorting and processing samples generally decreases as sample unit area is reduced.

Characteristics of Available Gear

Gear commonly used to estimate densities of estuarine populations may be separated into three major categories: towed nets, passive gear, and enclosure samplers (Table 1). Each has its advantages and limitations, which we discuss below. Entanglement gear (gill nets and trammel nets) are also widely used in estuaries, and are useful for collecting qualitative samples (e.g., for estimating growth rates, diet analysis, etc.) or documenting the movement of some fishes (e.g., Kleypas and Dean 1983; Sogard et al. 1989a,b). However, entanglement gear are generally not suitable for estimating population densities of small fishes and crustaceans.

Towed Nets

Commonly-used gear, such as trawls and seines, that use the area-swept method to estimate animal densities usually have low catch efficiencies (Loesch et al. 1976; Orth and van Montfrans 1987). Catch efficiencies of towed nets vary with the species and size of the targeted animals (Kjelson and Johnson 1978; Lyons 1986; Hartman and Herke 1987; Parsley et al. 1989; Allen et al. 1992; Millar 1992). For example, catch efficiencies of otter trawls have been measured for small brown

TABLE 1. List of available gear for sampling nekton in shallow estuarine habitats, and advantages and disadvantages of each type. CE = catch efficiency, RE = recovery efficiency, SUA = sample unit area.

Gear Type	Advantages	Disadvantages
Towed nets		
Otter trawl	Easy to use Clean samples Large SUA	Low and variable CE Ineffective in vegetation and shallow water SUA can be difficult to define Gear standardization very difficult Numerous attributes influence CE
Beam Trawl	Easy to use Clean samples Large SUA	Low and variable CE Ineffective in vegetation
Bottom Sled	Useful for unconsolidated bottom Easy to use Clean samples	Low and variable CE Ineffective in vegetation Gear standardization difficult
Surface trawl	Useful for unconsolidated bottom Easy to use Clean samples	Low and variable CE Ineffective in vegetation Gear standardization difficult
Seine	Easy to use Clean samples Large SUA	Low and variable CE Ineffective in vegetation/over soft substrate SUA can be difficult to define
Passive samplers		
Channel net[a] Fyke net	Large SUA	Recovery low for some species SUA can be difficult to define Gear avoidance at high tidal stages, in swift currents Samples integrated over space and time Stationary: fixed sample sites
Flume net[b]	RE is measurable and generally high Clean samples Large SUA	Restricted to intertidal Must include habitats near marsh edge Samples integrated over space and time Stationary: fixed sample sites Added structure may attract nekton in unvegetated habitats
Breder trap Pit trap Light trap	Easy to use Clean samples Relatively inexpensive to construct and maintain	Low and variable CE Extremely species selective CE difficult to measure SUA poorly defined, variable
Enclosure samplers		
Encircling net[c] Block net Purse seine[d]	RE is measurable Large SUA	Variable RE, dependent on method of sample removal CE low for some species/habitats Ineffective in vegetation
Flume Weir[e]	RE is measurable and generally high Clean samples Large SUA Not limited by shallow water	Restricted to intertidal Added structure may attract nekton in unvegetated habitats Small number of samples/tidal cycle Stationary: fixed sample sites
Drop Net[f]	RE is measurable and generally high Not limited by shallow water	Small SUA Added structure, shadow effect Stationary: fixed sample sites
Throw Trap[g]	Easy to use RE is measurable and generally high Relatively inexpensive to construct and maintain	Small SUA Ineffective in thick vegetation
Drop Sampler[h]	RE is measurable and generally high Effective in most shallow estuarine habitats	Small SUA Limited to habitats directly accessible with shallow draft boat

TABLE 1. Continued.

Gear Type	Advantages	Disadvantages
Pop Net[i]	RE is measurable and generally high Clean samples Relatively inexpensive to construct and maintain	Added structure may attract nekton in unvegetated habitats Difficult to deploy in some habitats, e.g., thick emergent vegetation, oyster reef RE dependent on removal method
Bottomless Lift Net[j]	RE is measurable and generally high Clean samples Not limited by shallow water Relatively inexpensive to construct and maintain	Restricted to intertidal Small SUA Small number of samples/tidal cycle Stationary: fixed sample sites

References describing selected gear are as follows:
[a] = Cain and Dean (1976), Hettler 1989, and Rountree and Able 1992.
[b] = McIvor and Odum 1986.
[c] = Lambou (1959).
[d] = Hunter et al. (1966).
[e] = Kneib (1991).
[f] = Hellier (1958).
[g] = Wegener et al. (1973) and Kushlan (1974).
[h] = Zimmerman et al. (1984).
[i] = Bagenal (1974).
[j] = Rozas (1992).

shrimp at 17.5–52.9% (Loesch et al. 1976), 17% (Zimmerman et al. 1986), and 49% (Minello et al. 1991). Extremely low catch efficiencies for trawls sampling spot (*Leiostomus xanthurus*) (6%), Atlantic croaker (*Micropogonias undulatus*) (26%), and anchovies (*Anchoa* spp.) (7%) have also been reported (Loesch et al. 1976; Minello et al. 1991). Average seine catch efficiencies for striped killifish (*Fundulus majalis*) (53%), Atlantic menhaden (*Brevoortia tyrannus*) (52%), white mullet (*Mugil curema*) (40%), striped mullet (*Mugil cephalus*) (33%), mummichog (*Fundulus heteroclitus*) (27%), and spot (23%) were estimated using standardized methods to sample an isolated marsh pool at low tide (Allen et al. 1992). If these catch efficiencies were stable, appropriate corrections could be made to estimate animal density; unfortunately, the efficiencies appear to be highly variable (Allen et al. 1992; Kuipers et al. 1992).

Catch efficiencies of towed nets are particularly difficult to stabilize because they are influenced by many factors. In addition to the behavior and size of the target species and numerous environmental factors, gear effectiveness of otter trawls also may vary with the method of rigging, mesh material and size, sound generated by boat and gear, towing speed and direction, tow duration, and the method of net retrieval (Kashkin and Parin 1983; Thayer et al. 1983; Carothers and Chittenden 1985; Creutzberg et al. 1987; DeAlteris et al. 1989; Millar 1992; Engas 1994; Workman et al. 1995). Further, some gear properties that affect catch efficiency change during a tow (e.g., size of otter trawl mouth opening, Koenig and Colin 1995), and therefore, catch efficiency may vary during sample collection as well as between samples (Engas 1994). With the aid of acoustic equipment, Wathne (1977) found that trawls performed erratically (i.e., they were off the bottom for substantial parts of a tow, or the wing spread fluctuated) in as many as 25% of tows. Any modification of the gear that reduces the number and degree of variations affecting efficiency should improve catch efficiency and gear precision and make standardization more tractable. For example, the mouth opening of a beam trawl is fixed, which improves the efficiency of this device relative to that of the otter trawl (Zimmerman et al. 1986; Kuipers et al. 1992).

A related and more insidious problem is that catch efficiency can vary with environmental characteristics, and often these characteristics are related to the treatments being measured in a sampling design. Unless this bias is identified and corrected, differences in density estimates attributed to species' preferences may simply be a reflection of a systematic shift in gear efficiency. For example, the effect of vegetation on catch efficiencies of trawls and seines is significant, and studies comparing several estuarine habitats where emergent or submerged vegetation is present have shown that abundances cannot be accurately measured in vegetation using towed nets (Miller et al. 1980; Howard and Lowe 1984; Gray and Bell 1986; Leber and Greening 1986; Orth and van Montfrans 1987). Differences in turbidity also have been shown to affect the catch efficiency of trawls for small fishes (Nielson 1983). In addition, bottom type (organic content, topography, sediment texture), sea state, water depth, and even temperature appear to affect the efficiency of trawls and seines (Herke 1969; Hartman and Herke 1987; Allen et al. 1992; Engas 1994). Furthermore, in shallow water, propeller turbulence can create unwanted disturbance and suspend sediment and other debris, which may clog a trawl, thus increasing net avoidance (Rogers 1985; Hartman and Herke 1987). A variety of modifications to towed nets have been developed to reduce specific problems related to catch efficiency, but these modifications do not solve all problems. Surface trawls mounted on the bow of a boat may overcome problems associated with propeller turbulence in shallow water and afford greater maneuverability in marsh channels (Herke 1969; Rogers 1985), but these devices must be positioned several centimeters above the bottom, and thus may under-sample epibenthic animals. A bottom sled may be towed over unconsolidated bottom where an otter trawl or seine cannot be used (Pullen et al. 1968), but this gear is also plagued by low and variable catch efficiency and is much less effective in vegetated habitats or areas containing debris or other structure. Juvenile penaeid shrimp often avoid capture in nets because they are burrowed in the substrate (Vance and Staples 1992), thus all the environmental factors that affect shrimp burrowing (time of day, incident light, turbidity, substrate type, predators, hunger level) may influence catch efficiency of penaeid shrimp. Therefore, to make valid comparisons among sites and habitats using samples from gear with low catch efficiency, abundance estimates must be adjusted to correct for site-related differences in gear catch efficiency. These corrections are difficult to estimate, but could be made for each site-habitat combination by making limited comparisons with gear known to have a high catch efficiency in that habitat.

The major advantages of using seines and trawls are their apparent ease of use. In addition, samples are usually relatively free of debris, and sample unit areas can be large (Table 1). However, these advantages cannot overcome the serious problems posed by low and highly variable catch efficiency, difficulty in estimating catch efficiency or standardizing the gear, and extremely low catch efficiency in some major estuarine habitats (e.g., emergent marsh, seagrass, shallow water, soft bottom).

PASSIVE SAMPLERS

The flume, channel net, and fyke net are examples of passive samplers commonly used in shallow estuarine areas. Channel nets and modified versions of this gear are placed in tidal channels to collect nekton on falling tides when aquatic organisms swim out of marshes or mangroves (Lewis et al. 1970; Cain and Dean 1976; Hodson et al. 1981; Rountree and Able 1992). Flumes, fyke nets, and variations of these devices also are designed to use tidal dynamics to collect samples in estuaries; they have been used to sample nekton both on the vegetated marsh surface and within small marsh creeks (McIvor and Odum 1986; Rozas et al. 1988; Hettler 1989).

The catch efficiency of these devices is unknown, mainly because gear avoidance is difficult if not impossible to measure. In addition, density estimates of target species are not easy to determine because the size of the sample area is difficult to define (Kneib 1991). Gear avoidance may be significant, especially at high tidal stages, when animals could swim over flume and fyke net walls or into the marsh to avoid channel and block nets. Animals can also avoid capture by remaining in small depressions in channels or on the marsh surface at low tide (Bozeman and Dean 1980; Kneib 1991; Rountree and Able 1992; Peterson and Turner 1994). The effect of this avoidance on catch efficiency depends on the degree that the channel or marsh drains at low tide. Catch efficiency also will depend on the mesh size of netting used to construct the gear. Recovery efficiencies of 53–80% for fishes and 30–46% for shrimps have been reported for the flume (McIvor and Odum 1986; Wenner and Beatty 1993).

One major advantage of these gear is that the sample unit area can be large (Table 1). In addition, samples often contain little detritus, and recovery efficiencies (at least for the flume) can be easily measured. Effective sampling, however, depends on tides carrying nekton into the net and completely draining the sampled area. Therefore, these gear can only be used to sample intertidal habitats and are unsuitable for general use in some habitat comparison studies. Passive gear may be difficult or impossible to use in unpredictable or microtidal systems or in areas that are not completely drained at low tide (McIvor and Odum 1986). Because careful attention must be paid to topography when placing these devices in a marsh or channel (e.g., to avoid areas that hold water at low tide), randomly selecting sample sites is often difficult. In addition, these gear sample continuously over a tidal cycle and integrate samples over time and space; therefore, it is difficult to relate samples to specific times or habitats (Kneib 1991). Other limitations in shallow estuarine habitats are more gear specific. For example, using a flume on unvegetated tidal flats adds a significant amount of artificial structure to the habitat, and structure will often attract animals and bias estimates. Density estimates made from samples taken with flumes and other nets with walls may also be biased because these gear block access to the area sampled from all but one direction (McIvor and Odum 1986).

Traps (e.g., Breder traps, pit traps, and light traps) might also be included under the category of passive samplers. The Breder trap (Breder 1960) has been used in salt marshes and mangroves (Sargent and Carlson 1987; LaSalle et al. 1991) and consists of a clear plastic box with a funnel-like entrance that allows fish to swim in (e.g., on a falling tide as they exit the marsh or mangrove area) but not out. Pit traps function similarly (Kneib and Stiven 1978) in that organisms leaving a marsh on a receding tide may take refuge in the trap (an open pit or bucket placed below the marsh surface). All of these gear, however, should probably be categorized as collecting devices rather than sampling devices, because they are highly selective in the species and size of animals entrapped. In addition, the sample area cannot be defined and is likely to vary depending upon habitat characteristics (e.g., plant stem density, water depth, microtopography, tidal regime).

Enclosure Samplers

This category includes a large number of sampling devices (Table 1): encircling/block net (Lambou 1959), purse seine (Hunter et al. 1966), drop net (Hellier 1958), throw trap (Wegener et al. 1973; Kushlan 1974), drop sampler (Zimmerman et al. 1984), pop net (Bagenal 1974), flume weir (Kneib 1991), pull-up net (Higer and Kolipinski 1967), and bottomless lift net (Rozas 1992). However, all are used similarly to rapidly enclose a sample unit area of known size from which animals are subsequently removed using a variety of methods (e.g., dip netting, seining, pump filtration, poisoning, and pursing).

Enclosure samplers appear to have generally high catch efficiencies; although efficiencies depend on gear type, method used to remove animals from the enclosed sample area, target species, and environmental conditions (especially water clarity). Kushlan (1981) estimated a catch efficiency of 70–76% for a 1-m^2 throw trap by sampling an enclosed area in which the total population was later estimated following an application of rotenone. For a 0.5-m^2 portable drop trap, Pihl and Rosenberg (1982) estimated catch efficiency as 97% for a shrimp and 98% for a goby by sampling a 16-m^2 enclosed area after a known density of animals had been added. A catch efficiency of 96% for a 2.6-m^2 drop sampler was estimated by sampling a small pond into which a known density of penaeid shrimp had been added (Zimmerman et al. 1986). For a 14.5-m^2 pop net, Larson et al. (1986) estimated a catch efficiency of 94–100% by observing and counting the number of fish that avoided capture after triggering the net in a swimming pool and in a reservoir during periods of high water clarity.

Enclosure devices are generally much more efficient than towed nets for sampling small organisms in shallow water. In a direct comparison with a 2.6-m^2 drop sampler in shallow unvegetated estuarine habitat, three types of towed nets were found to be only 17% (3.7-m otter trawl), 33% (5.5-m bag seine), and 82% (1-m beam trawl) as efficient for catching penaeid shrimp (Zimmerman et al. 1986). In a similar comparison, estimates of penaeid shrimp densities obtained with a 1.0 m × 0.5 m beam trawl were an order of magnitude lower than those obtained with a 0.8 m × 0.8 m drop trap (Vance et al. 1994). Both density (0.5 > fish m^{-2} versus 9.0 fish m^{-2}) and biomass (2 > g m^{-2} versus 15 g m^{-2}) estimates of fishes derived from bag seine samples were significantly less than those determined from portable drop net samples (Gilmore et al. 1978). Similar results were reported in other studies comparing catches of enclosure nets and seines (Kjelson and Johnson 1973; Kjelson et al. 1975; Freeman et al. 1984; Serafy et al. 1988; Fossa 1989; Connolly 1994).

Measuring the two components of catch efficiency (recovery efficiency and capture efficiency) for enclosure gear is practicable. The efficiency of recovering animals from the enclosed sample area can be easily measured (e.g., through simple tagging procedures) after the sampler has been deployed. Recovery efficiencies have been reported as follows: 91–98% (Zimmerman et al. 1986) and 82% (Sheridan 1992) for 2.6-m^2 drop sampler; 93–100% for 1-m^2 (Rozas and Odum 1987), 44–66% for 1.5-m^2 (Wenner and Beatty 1993), and 85–100% for 2-m^2 (Rozas and Reed 1994) throw traps; 42–100% for 100-m^2 flume weir (Kneib 1991); 32–93% for 6-m^2 bottomless lift net (Rozas 1992); and 50–100% for 25-m^2 pop net (Connolly 1994). Recovery efficiencies can be used to estimate capture efficiencies for enclosure gear by first estimating catch efficiency using one of the methods described above (e.g., Larson et al. 1986; Zimmerman et al. 1986) and then dividing catch efficiency by recovery efficiency.

The wide range in recovery efficiencies is due mostly to species differences and to the effectiveness of different methods used to recover the enclosed organisms (Matlock et al. 1982). In general, small, epibenthic species are much more difficult to remove from sampling devices than large, pelagic or semipelagic organisms (Kjelson and Johnson 1973; Gilmore et al. 1978; Kneib 1991). For example, recovery efficiencies for daggerblade grass shrimp *Palaemonetes pugio* in a flume weir increased with the animal's total length: 15–19 mm

= 42%, 20–24 mm = 47%, 25–29 mm = 55%, and > 30 mm = 72% (Kneib 1991). However, even adult grass shrimp, an epibenthic organism, are removed less efficiently than pelagic species; almost complete removal from enclosure nets has been reported for fishes such as spot (97%; Kneib 1991) and striped mullet (93%; Rozas 1992). Pursing the enclosure net or using a dip net or seine to remove animals from a large sample area may be less efficient than using a bar seine or other net designed to fit snugly against the sides of the sample enclosure (Jones 1965; Charles-Dominique 1989; Dewey et al. 1989; Connolly 1994). Seining inside a large enclosure is not an effective means of removing organisms, especially in vegetation (Moseley and Copeland 1969; Robblee and Zieman 1984). Adding rotenone or other toxicants inside the sampler may increase recovery efficiency for some animals (Matlock et al. 1982; Czapla 1991; Baltz et al. 1993); however, the effectiveness of these poisons varies with different taxa (Gilmore et al. 1981; Johnson et al. 1988; Dudgeon 1990). Removing and filtering water from inside the sample enclosure also increases recovery efficiency by exposing animals that would otherwise avoid capture and by driving burrowed organisms out of the substrate. This may be accomplished naturally by tidal action in intertidal habitats (e.g., flume weir, Kneib 1991; and bottomless lift net, Rozas 1992) or by pumping (e.g., drop sampler, Zimmerman et al. 1984). Recovery efficiencies of > 90% for juvenile penaeid shrimp were achieved by pumping water from a drop sampler (Zimmerman et al. 1986); however, efficiencies were only 44–66% for grass shrimp when water was not completely removed from a similar sampling device (Wenner and Beatty 1993). Species that remain on the marsh surface in small depressions at low tide are not efficiently removed from large, tidally drained enclosures in a single tidal cycle (Kneib 1991). Removing vegetation from within the enclosed area may also increase recovery efficiency but is feasible only in relatively small enclosures. Net mesh size of enclosure walls also affects recovery efficiency; using gear constructed with large mesh netting will allow small organisms to escape (Hellier 1958). This problem should be avoided by constructing nets with a mesh size small enough to collect the smallest organism targeted in a study (Gilmore et al. 1978). Recovery efficiency generally decreases as the size of the enclosure increases, especially in vegetated habitats and when water in the enclosure cannot be removed (Shireman et al. 1981; Miller et al. 1990). Because sample unit size also interacts with environmental heterogeneity and animal distributions within habitats, there is a tradeoff between recovery efficiency and sampling precision. Increasing the sample unit area decreases recovery efficiency but increases sampling precision, especially for rare or highly-clumped organisms. Finding the optimum sample unit area where a balance is struck between these two opposing factors is an important aspect of gear selection (Pringle 1984; Palmer and White 1994).

Although enclosure samplers yield quantitative data, some of these gear are not suitable for all shallow estuarine habitats. Flume weirs and lift nets depend on tidal action and can only be used in intertidal habitats. Furthermore, their use on unvegetated substrates would bias samples because they add too much structure to the habitat (Kneib 1991; Rozas 1992). Drop nets may also bias samples by altering the habitat with their presence; this problem becomes even more acute when drop nets are used repeatedly to sample the same area (Hoese and Jones 1963; Kushlan 1974). Damage to sampled areas also may be of concern in sensitive habitats (e.g., created and restored salt marshes, seagrass beds). Enclosure techniques, however, can generally be modified to reduce or eliminate permanent impacts to such habitats.

The confounding problem of habitat characteristics affecting both animal density and gear efficiency, which is common for towed nets, can be avoided if the catch efficiency of the sampling gear is very high in the targeted habitats. Throw traps and drop samplers, for example, appear to have high catch efficiencies that do not vary substantially in the presence of vegetation (Zimmerman et al. 1986). These enclosure devices have relatively few associated variables that influence catch efficiency, and standardizing sampling methods is easy and straight forward. The time required to collect samples with a throw trap or drop sampler varies considerably depending on substrate type, but under most conditions, it is relatively short (i.e., approximately 15–30 min sample^{-1}); therefore, it is feasible to collect 15–30 samples d^{-1}. In addition, throw traps and drop samplers generally require no modification of the habitat prior to sampling; they sample the entire water column; and they are easy to use and inexpensive to construct, maintain, and operate.

Like all current sampling devices, throw traps and drop samplers have drawbacks and limitations. The area enclosed by these samplers is often small (1–3 m^2), although increasing the number of samples can generally compensate for this limitation. In many cases the small sample unit area can be viewed as an advantage, because more samples are required and the target habitat may be better represented. Throw traps and drop samplers are also limited by water depth and vegetation density. Drop samplers are generally limited to water

TABLE 2. Gear recommendations for quantitative sampling of small nekton in shallow estuarine habitats based on the gear characteristics listed in Table 1. Recommendation: R = highly recommended; C = conditionally recommended (only recommended under suitable environmental conditions or if the original design of the gear is modified to improve catch efficiency); N = not recommended.

	Major Habitats				
Gear Type	Non-vegetated Subtidal	Non-vegetated Intertidal	Seagrass or SAV	Tidal Marsh	Oyster Reef
Encircling or block net	C	C	C	N	C
Purse seine	C	C	N	N	N
Flume weir	N	N	N	R	N
Drop net	N	N	C	C	C
Throw trap	R	R	R	C	C
Drop sampler	R	R	R	R	R
Pop net	C	C	R	N	C
Bottomless lift net	N	N	C	R	C

depths less than 1.5 m, but throw traps have been used to sample areas 1.5–1.8 m deep (Rozas and Reed 1994). Throw traps are generally too light to function properly in dense vegetation, and if weight is increased enough to cut through the vegetation, the gear may be too heavy to throw. This problem has been overcome by development of the drop sampler, which is supported by a boom attached to a boat and can be built with heavier material than throw traps. Attaching a metal skirt to the bottom of a drop sampler also helps cut through even the thickest marsh vegetation. Woody vegetation also can be sampled with a drop sampler; red mangroves were sampled after clearing the prop roots around the perimeter of each sample site (Sheridan 1992). Use of a drop sampler is restricted to areas accessible with a shallow-draft vessel, and this restriction can prevent sampling emergent marsh if the water is only a few centimeters deep. However, we have successfully used this gear in areas up to 35 m from the marsh-water interface by pushing a shallow-draft boat into a salt marsh flooded by as little as 15 cm of water (Minello et al. 1994).

In summary, we recommend strong consideration of enclosure samplers for estimating densities of small fishes and crustaceans in shallow estuarine habitats (Table 2). These samplers provide quantitative data; and catch efficiencies are high, relatively constant, and measurable. Throw traps and drop samplers are particularly useful in studies comparing different shallow estuarine habitats because, unlike towed nets, their catch efficiencies do not appear to diminish in vegetated habitats (Zimmerman et al. 1986). These devices have been used to sample a variety of shallow water habitats including oyster reefs, tidal marsh, mangroves, submerged vegetation, and unvegetated subtidal bottom (e.g., Bass and Guillory 1979; Pihl and Rosenberg 1982; Zimmerman et al. 1984, 1989; Thomas et al. 1990; Sheridan 1992; Rozas and Minello 1998). Although some enclosure devices may be limited to particular habitats (Table 2), all collect quantitative data in the habitat for which they are suited. If a gear provides quantitative data from a sample area of known size, catch per sample can be easily converted to density (animals per area of habitat); and density estimates can be used as the basis for habitat comparisons, even when different types of quantitative gear are used in various habitats.

No sampling device is completely unbiased, and an evaluation of gear limitations should be done routinely prior to selecting sampling gear for studies to estimate population densities. Additional research is needed to estimate catch efficiency over a range of environmental conditions likely to be encountered in shallow estuarine habitats (Kjelson 1977; Kjelson and Colby 1977). Modifications of currently-used gear and development of new sampling methods are also needed to improve catch efficiency.

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Glossary

Accuracy—the closeness of a mean density estimate to the true mean density of animals in a habitat.

BIAS—systematic error (positive or negative) in estimating density or population size caused by the sampling method.
CATCH EFFICIENCY—the proportion of target animals within the sample unit area that is collected with the sampling device and enumerated (= capture efficiency × recovery efficiency).
CAPTURE EFFICIENCY—the proportion of target animals within the sample unit area that is enclosed or captured by the gear.
GEAR AVOIDANCE—to escape capture by active or passive means.
HABITAT—areas where fishes and decapod crustaceans live that are generally characterized by hydrology, substrate type, and dominant vegetation.
INEFFECTIVE—gear catch efficiency is so low that gear use is inappropriate.
PRECISION—the closeness of repeated density estimates taken from the habitat.
QUANTITATIVE—accurate and precise.
RECOVERY EFFICIENCY—the proportion of target animals that is recovered from the sampling device and enumerated.
SAMPLE SIZE—number of samples collected.
SAMPLE UNIT AREA—area covered by the sampling device; area used to convert abundance to density estimate.
SAMPLING SITE—location of one sample unit or one deployment of gear.
SAMPLING AREA—area identified for study that may include several habitats or strata.
STANDARDIZATION—the technique of making a piece of gear function similarly each time it is used.
STRATUM, STRATA (pl.)—specific area or areas designated for sampling and statistical analyses.